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GL-TR-89-0278

AMBIGUITY BOOTSTRAPPING TO DETERMINE GPS ORBITS AND BASELINES

Charles C. Counselman III

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

10 October 1989

Scientific Report No. 6

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GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AIR FORCE BASE, MASSACHUSETTS 01731-5000

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THOMAS P. ROONEY, Chief
Contract Manager
Geodesy and Gravity Branch

FOR THE COMMANDER

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 October 1989	Scientific No. 6

4. TITLE AND SUBTITLE

Ambiguity Bootstrapping to Determine GPS Orbits and Baselines

5. FUNDING NUMBERS

61102F
2309G1BN

Contract F19628-86-K-0009

6. AUTHOR(S)

Charles C. Counselman, III

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Geophysics Laboratory
Hanscom AFB
Massachusetts 01731-5000

Contract Manager: Thomas P. Rooney/LWG

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

GL-TR-89-0278

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

SEE NEXT PAGE

Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	
By	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
A-1	

14. SUBJECT TERMS

Space Geodesy
NAVSTAR Global Positioning System
GPS
Satellite Geodesy
Radio Positioning
Radio Interferometry

15. NUMBER OF PAGES

14

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Second Symposium on GPS Applications in Space, Air Force Geophysics Laboratory, October 10, 1989.

Ambiguity Bootstrapping to Determine GPS Orbits and Baselines

CHARLES C. COUNSELMAN III

Department of Earth, Atmospheric, and Planetary Sciences
and Center for Space Research
Massachusetts Institute of Technology, Cambridge

Abstract: For GPS satellite-orbit and interstation-baseline determination, the most accurate observable available is carrier phase, differenced between observing stations and between satellites to cancel both transmitter- and receiver-related errors. For maximum accuracy, the integer cycle ambiguities of the doubly differenced observations must be resolved. To perform this ambiguity resolution, Counselman (*Eos, 68*, 1238, 1987) proposed a bootstrapping strategy. This strategy requires the tracking stations to have a wide ranging progression of spacings. By conventional "integrated Doppler" processing of the observations from the most widely spaced stations, the orbits are determined well enough to permit resolution of the ambiguities for the most closely spaced stations. The resolution of these ambiguities reduces the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which further reduces the orbital uncertainty.

Abbot and Counselman (*ibid.*, 1987) and Counselman and Abbot (*JGR, 94*, 7058-7064, 1989) applied this strategy to a network of six tracking stations spaced by 71 km, 245 km, ..., up to 4000 km. Resolving ambiguities for the shortest, 71-km baseline made it possible to resolve them for the next-longer, 245-km baseline, and reduced both the formal and the true errors of determining the GPS satellite orbits by a factor of 2. The precision of baseline determination was also significantly improved.

Ionospheric refraction interferes with ambiguity resolution, by systematically biasing the doubly-differenced phase observations. However, the signature of ionospheric refraction resembles that of orbital position error; either effect, although time-variable, is spatially coherent, characterized by a nearly uniform gradient across a few-hundred-kilometer-size tracking network. Thus, the same bootstrapping principle which facilitates ambiguity resolution in the presence of orbital uncertainty, can be effective in the presence of significant ionospheric refraction.

To test this prediction, Abbot, Counselman, and Gourevitch (*Eos*, in press, Fall 1989) analyzed GPS observations from a recent period of high solar activity, with daily observation periods spanning the morning hours during which the ionosphere varies most rapidly. The ionospheric refraction effects in these observations (5 am - noon, November 1988, in Texas) were some 20 times stronger than in the night-time, April 1985, observations originally studied by Abbot and Counselman.

Using a very simple, five-parameter, ionospheric model, Abbot *et al.* processed observations from 12 dual-band receivers which were arranged in a logarithmic "Nautilus" spiral with spacings from 10 to 320 km. The use of this model increased the interstation baseline length for which ambiguities could be resolved by a factor of two (to the maximum length available). Observations on successive days were processed independently; *i.e.*, the ionospheric parameters, the position coordinates of nine receiving stations (three stations served as "fiducials"), and all the orbital elements of each satellite were determined from "single-day" arcs. The standard deviations of the horizontal station-position coordinate estimates were 2.5-4 mm, or 2-3 parts in 10^8 of the distance to the nearest fiducial.

The doubly differenced carrier phase observable:

$$\Delta\Delta\phi_{kq}{}^{ij} = -(1/\lambda)\,\Delta\Delta r_{kq}{}^{ij} + N_{kq}{}^{ij}$$

$\Delta\Delta r_{kq}{}^{ij}$ is the doubly differenced range between satellites i, j and stations k, q;

λ is the carrier wavelength; and

$N_{kq}{}^{ij}$, known as the "ambiguity parameter" or the "bias," is an **integer number of cycles.**

(from Counselman, C. C., Resolving carrier phase ambiguity in GPS orbit determination, *Eos Trans. AGU*, *68*, 1238, 1987.)

AMBIGUITY BOOTSTRAPPING:

1. The tracking stations should have a **wide-ranging progression of spacings.**

2. Conventional processing of observations from the most widely spaced stations (without any ambiguity resolution) determines the orbits well enough to permit resolution of ambiguities for the most closely spaced stations.

3. The resolution of these ambiguities reduces the uncertainty of the orbit determination enough to enable ambiguity resolution for more widely spaced stations, which **further** reduces the orbital uncertainty,....

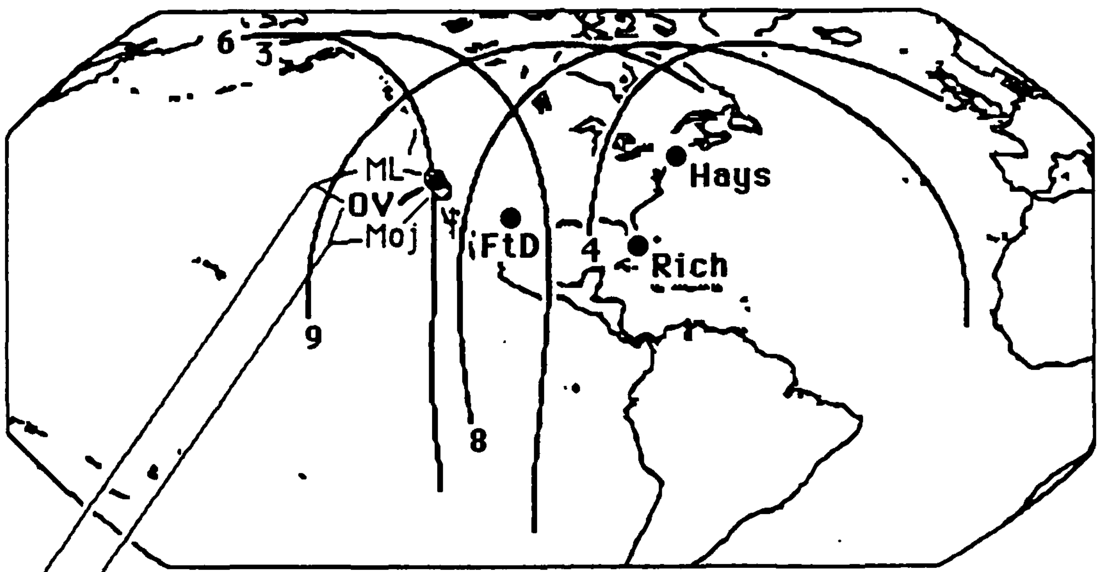
(From J. Geophys. Res., 94, 7058-7064, June 10, 1989)

Four widely spaced tracking stations:

OV, FtD, Rich, Hays

Two additional stations, very close to OV:

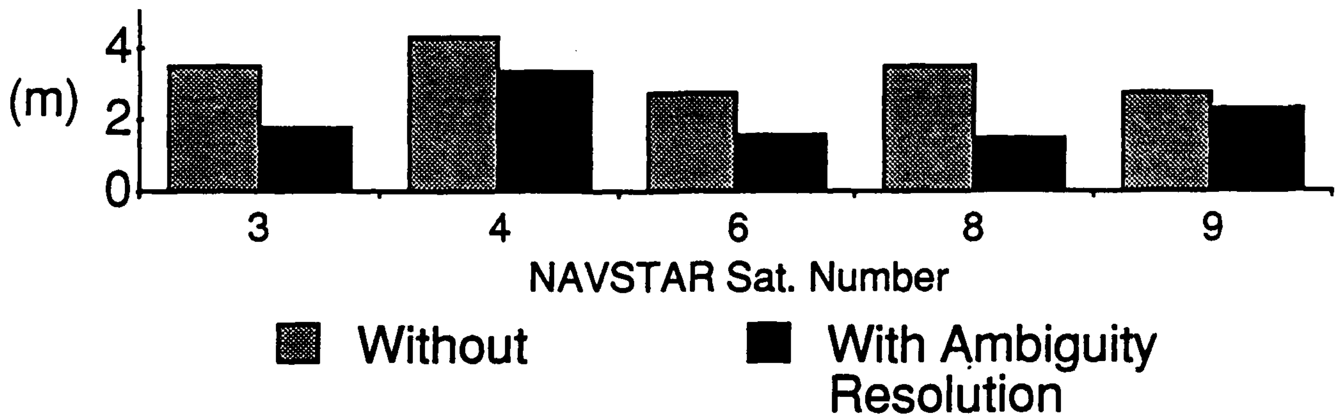
ML, Moj



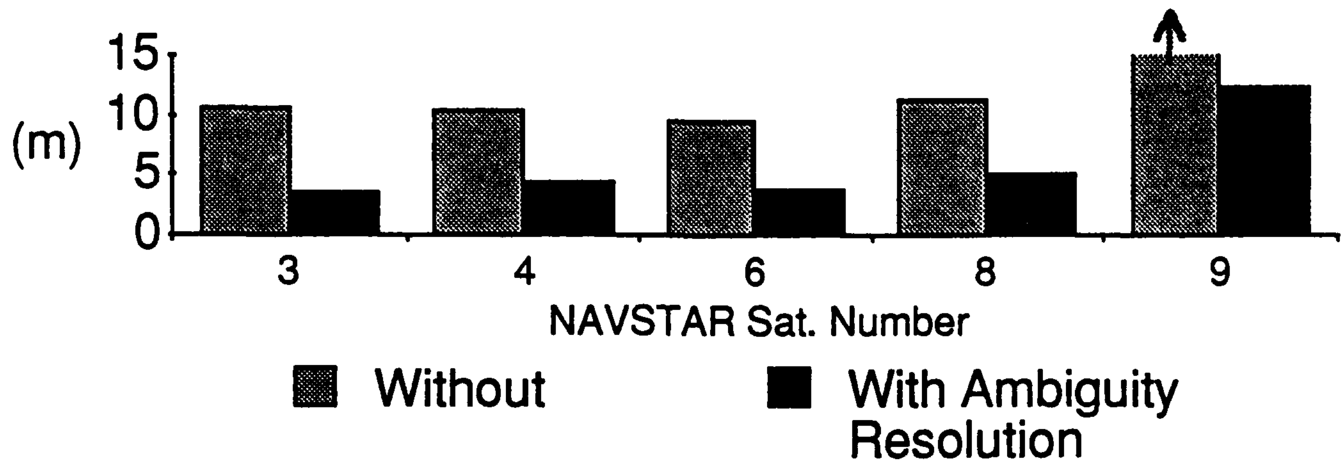
ML-OV distance < 2% of OV-Hays distance.

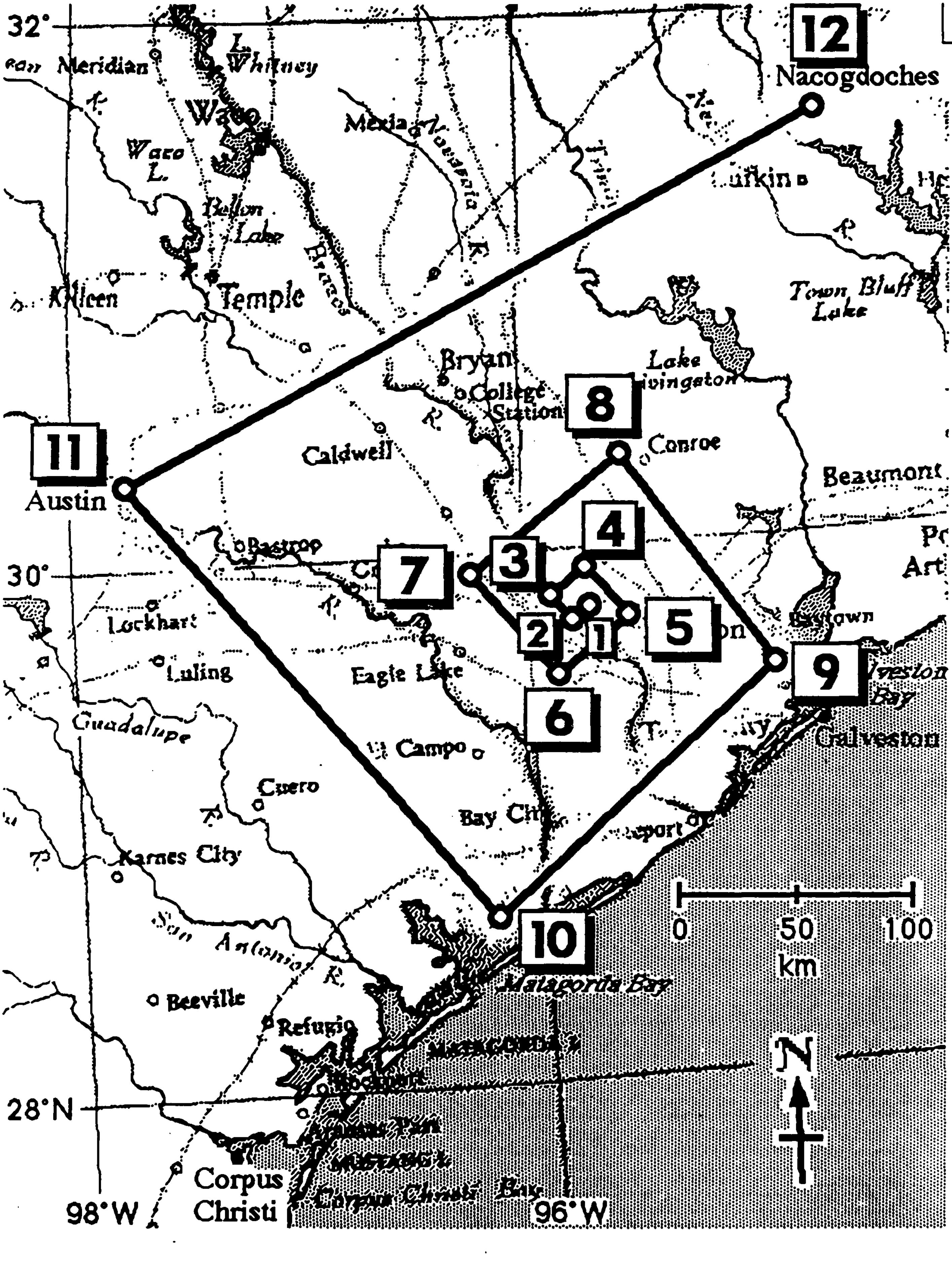
OV-Moj distance = 6% " " " ".

Formal Standard Errors of Orbit Determination
With and Without Ambiguity Resolution
for ONLY THE CLOSEST (<6%) Station-Pairs
(all stations' phase obs'ns equally precise)



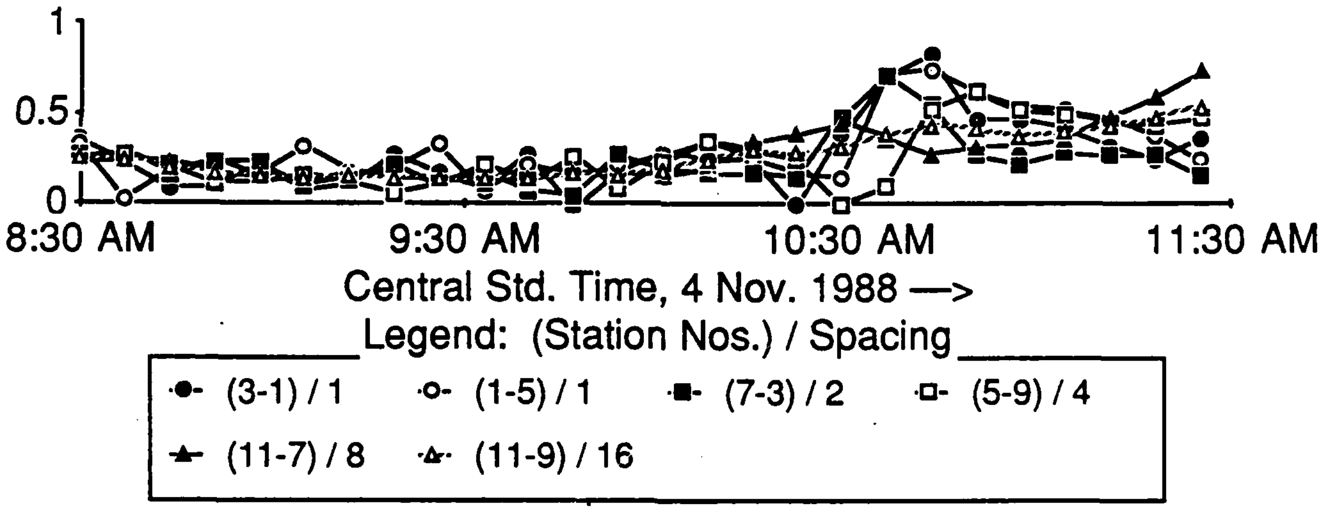
ACTUAL Peak Errors of Orbit Determination
With and Without Ambiguity Resolution
for ONLY THE CLOSEST (<6%) Station-Pairs
(all stations used in either case)

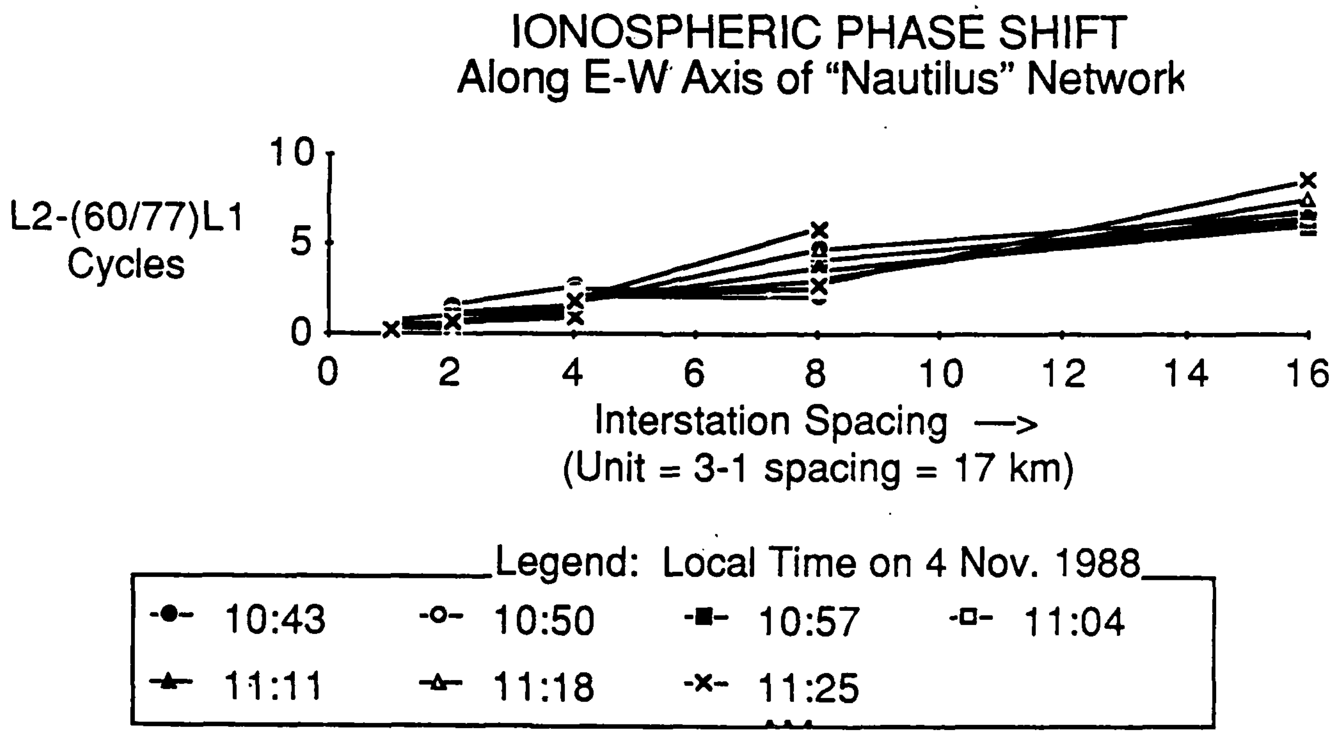




32°
30°
28°N
98°W
96°W
12
Nacogdoches
11
Austin
10
9
8
7
6
5
4
3
2
1
Meridian
L. Whitney
Waco
Waco L.
Belton Lake
Mexia
Killeen
Temple
Brazos
Bryan
College Station
Caldwell
Conroe
Lake Livingston
Lufkin
Town Bluff Lake
Beaumont
Bastrop
Lockhart
Luling
Guadalupe
Eagle Lake
Campo
Cuero
Bay City
Karnes City
San Antonio R.
Beeville
Refugio
Matagorda Bay
Galveston
Corpus Christi
Corpus Christi Bay
0
50
100
km
N

GRADIENT OF IONOSPHERIC PHASE-SHIFT
Along E-W Axis of "Nautilus" Network
[L2-(60/77)L1 Cycles Per Unit Station-Spacing;
NAVSTAR 8 - 10 Difference]




IONOSPHERIC PHASE SHIFT
Along E-W Axis of "Nautilus" Network
L2-(60/77)L1
Cycles
10
5
0
0
2
4
6
8
10
12
14
16
Interstation Spacing —>
(Unit = 3-1 spacing = 17 km)
Legend: Local Time on 4 Nov. 1988
10:43
10:50
10:57
11:04
11:11
11:18
11:25

STATION-POSITION (& ORBIT) DETERMINATIONS

Using observations from one day at a time, constraining just three fiducial-station positions, we estimated **independently for each day**

- all three position coordinates of each other station
- all six orbital elements of each satellite ("single day arcs")
- one tropospheric (zenith delay) parameter for each station except no. 1
- five ionospheric parameters [1 const. + 2x2 sin/cos(lat./lon.) coeff's]
- and a few receiver clock synchronization parameters,

and used bootstrapping to **resolve all ambiguities from scratch each day.**

Note: Antennas and receivers were replaced daily at all stations except nos. 5, 11, and 12.

STANDARD DEVIATIONS OF INDEPENDENT SINGLE-DAY DETERMINATIONS

from scatters of 17-d.o.f. samples (9 stns. on each of 3 days except for one receiver failure on one day):

LATITUDE	LONGITUDE
2.5 mm	4.0 mm

or, expressed as fractions of the distance to the nearest fiducial station (no. 10):

1.8×10^{-8}	2.9×10^{-8}

Formal Standard Errors of Orbit Determination
With the 240 x 320 km 'Nautilus' Network
(Single-Day Arc, 8 Nov. 1988)